AIAA, New York City, Jan. 20-22, 1964

[1964] 16p rep

HEAT-TRANSFER ANALYSIS OF ROCKET NOZZLES USING VERY HIGH TEMPERATURE PROPELLANTS

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N65-88991

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Code 2A

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For presentation at the AIAA Meeting on Aerospace Sciences, N.Y., 20-22 Jan. 1964

E-2351

ABSTRACT

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The Monte Carlo method is used as a basis for determining two-dimensional propellant temperature distributions and wall heat-transfer rates as functions of axial position in a nozzle of arbitrary shape. The propellant is considered to be at such elevated temperatures that radiation is the dominant mode of heat transfer, although the effect of convection is also considered. The propellant is assumed to be an absorbing-emitting gas with a constant absorption coefficient, and the effects of flow, variable heat-transfer coefficient, propellant heat capacity, and nozzle wall temperature are included.

Author

INTRODUCTION

Typical analyses of heat transfer in rocket nozzles take into account the effects of conduction and convection combined with the difficult problem of energy release by chemical reaction in the combustion chamber and nozzle. In recent concepts of rocket propulsion, such as the solid-core nuclear rocket or the gaseous core nuclear rocket, propellant temperatures under consideration have been reaching higher and higher levels. At these temperature levels the transport of heat by radiation becomes an important and perhaps an overriding factor in comparison to conduction or even convection [1, 2]. In nuclear rockets combustion per se is not encountered; however, consideration of radiant heat transport in absorbing-emitting gases as an important mechanism replaces the combustion problem by one that is more difficult in many respects.

Previous workers [3, 4] have considered the effect of radiation in rocket nozzles by assuming the propellant to be transparent to radiation and then by calculating the radiant interchange between various finite segments of the nozzle wall. The effects of the nontransparency of the gas and the interactions between the various modes of heat transfer were not taken into account.

Einstein [1] and Ragsdale and Einstein [2] considered the effect of radiation in a flowing gas with constant properties, but restricted the study to a finite, right circular cylinder.

A convenient tool for attacking radiant-heat-transfer problems involving real gases in complex geometries has recently been introduced [5]. This is the use of the Monte Carlo method, which is familiar in the solution of neutron-diffusion and free-molecule gas-dynamics problems. Its possible application to this type of problem was originally mentioned in [6], but has only recently been applied. Use of Monte Carlo makes the otherwise extremely complex problem attacked here soluble within reasonable limits of accuracy and digital computer time.

PROBLEM

The problem analyzed is the determination of the wall heat flux as a function of axial position and the two-dimensional propellant temperature distribution in a rocket nozzle operating under steady-state conditions. The propellant mean radiation absorption coefficient is considered to be a constant, and a nozzle wall heat-transfer coefficient is taken as an arbitrary function of axial position. The effect of propellant flow is considered, with an assumed initial slug flow profile.

Required initial conditions are the propellant mass flow rate and the temperature distribution at the nozzle inlet, the axial pressure distribution in the nozzle, and the propellant absorption coefficient and heat capacity.

Some assumptions are made that allow the neglect of conduction in the gas and along the nozzle walls - neglect of wavelength effects on radiation in the gas and neglect of radiant emission from the nozzle walls. The basis for these and other assumptions is discussed in the analysis.

METHOD OF ANALYSIS

The general computer program developed for this problem uses finite-difference equations to define the magnitude of radiant energy sources in the propellant on the basis of an assumed propellant temperature profile. Another section of the program then uses these sources and the known radiant energy assumed to be entering the nozzle from the gaseous core nuclear reactor to solve the radiation transfer by a Monte Carlo technique. From the energy emission thus determined for each gas element, a new temperature profile is found. This profile is then used as a new temperature estimate, and the procedure is repeated until convergence is obtained.

In more detail, the rate of energy emission from a gas volume element ΔV, adjacent to the nozzle wall, is found by a heat balance to be

$$4\kappa_{\Delta V}\sigma T_{\Delta V} = E_{\Delta V} + W_{\Delta V}C_{p,\Delta V}(T_{in} - T_{out}) - hA_W(T_{\Delta V} - T_W) \qquad (1)$$

where $\kappa_{\Delta V}$ is the gas absorption coefficient, assumed constant throughout the element, $W_{\Delta V}$ is the mass flow rate through the element, $(C_p)_{\Delta V}$ is the propellant heat capacity, also assumed constant throughout the volume element, and T_{in} and T_{out} are the temperatures of the propellant entering and leaving the element, respectively. The first term on the right is the rate of radiant energy absorption in the element. The last two terms are, respectively, the rate of energy entering the element by flow and the rate of energy loss by convection to the wall.

The term $E_{\Delta V}$, giving the absorption of radiant energy, is the most difficult term to evaluate. It is made up of radiant energy originating in other gas elements and radiant energy entering the rocket nozzle from the reactor chamber. Small contributions to $E_{\Delta V}$ are made by radiant energy emitted by the nozzle walls; however, this portion was ignored in the analysis since it is generally negligible in comparison to other energy terms.

A Monte Carlo technique, similar to that described in reference [5], was used to evaluate $E_{\Delta V}$. The two sources of radiant energy in the system were assumed to be composed of bundles of energy of finite size. These bundles were followed throughout the nozzle until final loss from the system. Each absorption of an energy bundle in a given gas element was tallied, and the energy thus absorbed made up a portion of the $E_{\Delta V}$ for that element.

The radiant sources in the gas were found by assuming that a propellant temperature drop could only be due to a loss of energy by radiation or convection from the element. Thus, the radiant source magnitude for an element is given by

$$q_{source} = W_{\Delta V} C_p (T_{in} - T_{out}) + E_{\Delta V} - hA_W (T_{\Delta V} - T_W) \tag{2}$$

With all the other terms in equation (1) known, $T_{\Delta V}$, the gas increment temperature, can be determined. If the element considered is not adjacent to a surface, the last (convection) term in equations (1) and (2) is not present.

With the temperature distribution obtained in this manner, a new set of sources is found from equation (2), and a new set of temperatures is computed. This procedure is followed until convergence.

To obtain the heat flux along the nozzle wall, the number of energy bundles striking the wall per unit area was simply multiplied by the energy per bundle, and this was added to the heat flux at the wall given by a convection term. A correction for radiant emission from the wall element was then subtracted so that the total energy flux at an elemental area on the nozzle wall was given by

$$\left(\frac{q}{A_W}\right)_{\Delta A} = \frac{E_{\Delta A}}{A_W} + h(T_{\Delta V} - T_W) - \sigma T_W^4 \tag{3}$$

COMPUTER PROGRAM

A condensed flow chart for the computer program is shown in figure 1 as an outline of the procedure used. The complete flow chart, including all equations, may be obtained by contacting the authors. The complete chart contains all the equations in a step by step flow scheme and a list of nomenclature.

The flow chart was translated for use on an IBM 7094 digital computer, as the Monte Carlo method depends on extremely fast repetitive solutions of simple equations.

The Monte Carlo method yields temperature distributions in which the individual temperatures have statistical fluctuations around a mean profile for each iteration. This leads to fluctuating heat sinks between iterations and consequent slow convergence. To avert this problem, constraints were placed on the calculated individual temperatures so that they could not exceed the peak inlet propellant temperature nor be less than the wall temperature. The guess for the temperature distribution for a new iteration was taken as an average of the distributions given by the two previous iterations. This average profile was used to calculate the radiant sources for the next iteration. The averaging procedure was similar to the introduction of a damping factor familiar in speeding the convergence of integrodifferential equations. Convergence of the temperature profiles was checked by increasing the number of energy bundles followed, by decreasing the propellant element size, and then by determining if the solution changed.

ASSUMPTIONS

It was necessary to make a series of assumptions in order to somewhat simplify the problem. They are

(1) No surface emission. The nozzle walls were considered to contribute no radiant energy to the system by emission. This is a reasonable assumption since the radiant energy entering the system by other means is at least an order of magnitude greater than that emitted by the cooled nozzle walls. However, a wall emission term is included in the heat balance equations used to obtain the wall heat flux.

(2) Perfectly absorbing walls. An assumption of black walls is conservative in that interest centers on the maximum heat flux to be encountered, and any decrease in surface absorptivity will decrease the heat-transfer rates at the surface.

(3) Incremental flow. The propellant entering the nozzle is assumed to maintain its entering radial mass flow distribution through the nozzle; that is, the same proportion of flow will remain in a given radial increment throughout the nozzle. This assumption was compared to a potential flow solution for

the nozzle used in the example presented later (fig. 2) and was found to be reasonable. The effects of extreme radial temperature profiles and pressure gradients on the flow distribution, however, leave the potential flow solution and, therefore, this assumption open to some question.

(4) Gray gas. The gas absorption coefficient is assumed independent of wavelength. In certain propellants, notably hydrogen, variations in the absorption coefficient are very large over the range of pressures and temperature encountered in a nozzle, while not so great over the wavelength range of interest. This lends some justification to this assumption. A further tacit assumption that the gas absorption coefficient does not vary over a mean free path is made, which in essence makes the radiation portion of this analysis a diffusion solution if variations in absorption coefficient are taken into account. Also, the absorption coefficient is assumed constant within a given gas element. Although allowance is made in the program for variation of absorption coefficient with temperature and pressure, it was taken as constant for all results presented herein.

(5) No conduction. The neglect of conduction as a heat-transfer mechanism in the propellant was considered justified on the basis of the work by Einstein [1], who showed it to be a negligible factor in similar problems. Conduction could have been considered by simply including it in equations (1) and (2).

(6) Axial symmetry. No circumferential variations in any physical quantities were considered.

(7) Convection not based on bulk propellant temperature. Rather than integrating each radial gas temperature distribution to obtain a bulk temperature, the convective heat transfer is based on the propellant temperature in the increment closest to the wall. Since it was expected that the radiant energy transfer would be the overriding mechanism, any error introduced here should be small.

SAMPLE PROBLEM

With the analysis developed in the preceding sections, the heat transfer to the nozzle walls and the gas temperature distribution for a typical case were computed. The conical nozzle shown in figure 3, which corresponds to a case studied by Robbins [4] for radiation through a stagnant transparent gas, was chosen, although the program will accept any nozzle shape.

Results in excellent agreement with those of Robbins were obtained for this limiting case, as shown in figure 4. The results fall somewhat below those of Robbins because the effect of radiant transfer from the nozzle wall to other elements on the wall was neglected herein.

To indicate the effect of the important parameters, this same nozzle shape was studied under simplified sample conditions. The input conditions used are representative of those expected in nozzles used in conjunction with gaseous core nuclear reactors [7].

The propellant is assumed to enter the nozzle at a constant bulk temperature of 13,000° R in a slug flow profile. The nozzle wall is taken to be at a temperature of 5000° R.

The first variable studied is the propellant radiation absorption coefficient $\overline{K}$. This parameter is assumed constant in the example, although, as mentioned previously, the program will accept it as a function of local propellant temperature and pressure. Figure 5 shows its effect on the heat transfer to the nozzle wall. As $\overline{K}$ is increased and the propellant becomes more optically dense, the peak heat flux increases and moves closer to the nozzle inlet. This effect is due to the strong absorption and reemission of radiant energy in the optically dense propellant at the entrance to the nozzle which traps energy that would otherwise pass through and be absorbed at the nozzle wall downstream.

Figure 6 shows the propellant temperature profile near the nozzle wall as flow and/or heat capacity of the propellant are increased. This effect is shown by increasing the parameter WC_p, the product of total flow rate and propellant heat capacity. The overall propellant temperature increases as WC_p is increased, since a smaller proportion of the propellant enthalpy is lost to the nozzle surface.

In figure 7 the change in heat-transfer rate to the nozzle wall with increasing WC_p is demonstrated. The overall level increases rapidly as WC_p is raised. As WC_p reaches very high values, the effect of flow predominates over the radiant energy entering the upstream end of the nozzle. The high flow rate, combined with the diverging geometrical shape past the nozzle throat, causes a second peak to occur in the heat flux. At higher flow rates than those studied, this peak may predominate.

Figure 8 compares the nozzle-wall heat flux at a high and a low WC_p before and after the addition of a typical convective heat-transfer coefficient given by

$$h = \frac{485}{(D)^{0.2}} \frac{\text{Btu}}{(\text{hr})(\text{sq ft})(^{\circ}\text{R})} \tag{3}$$

This coefficient was calculated from equations given by Bartz [8] for similar cases. Propellant properties were taken as those of hydrogen evaluated at 100 atmospheres and 13,000° R. The effect of convection on the total heat transfer is small.

CONCLUDING REMARKS

A method of analysis suitable for a group of nozzle heat-transfer problems in which the propellant enters at very high temperatures, so that radiation energy transfer is dominant, was presented.

For a simplified sample problem it was shown that the portion of total energy transfer to the nozzle wall due to radiation far outweighed that due to convection. Also, the peak flux occurred near the nozzle entrance early in the convergent portion rather than near the throat for the gray propellant assumed in the example. Both these results are in sharp contrast to those found in chemical rockets, where convective heat transfer predominates.

The level of heat fluxes encountered in the example, especially near the nozzle inlet, indicates that serious nozzle cooling problems may be encountered for mean propellant temperatures in the 10,000° to 15,000° R range, even if maximum temperatures exist only along the axis of the nozzle flow passage.

SYMBOLS

A_W	area of surface of axial nozzle element, sq ft
C_p	heat capacity of propellant, Btu/(lb)(°R)
D	local nozzle diameter, ft
$E_{\Delta A}$	rate of radiant energy absorption in a surface element, Btu/hr
$E_{\Delta V}$	rate of radiant energy absorption in a volume element, Btu/hr
h	convective heat-transfer coefficient, Btu/(hr)(sq ft)(°R)
q_{source}	radiative energy emitted by a source in a volume element, Btu/hr
T_{in}, T_{out}	temperature of propellant flowing into or out of a volume element, respectively, °R
$T_{\Delta V}$	temperature of a volume element, °R
T_W	nozzle wall temperature, °R
W	propellant flow rate through nozzle, lb/hr
$W_{\Delta V}$	propellant flow rate through volume element, lb/hr
ΔV	volume of element, cu ft

$\bar{\kappa}$ mean propellant radiation absorption coefficient, 1/ft

$\kappa_{\Delta V}$ propellant absorption coefficient in volume element, 1/ft

σ Stefan-Boltzmann constant, 1.714×10^{-9} Btu/(hr)(sq ft)($^{o}R^{4}$)

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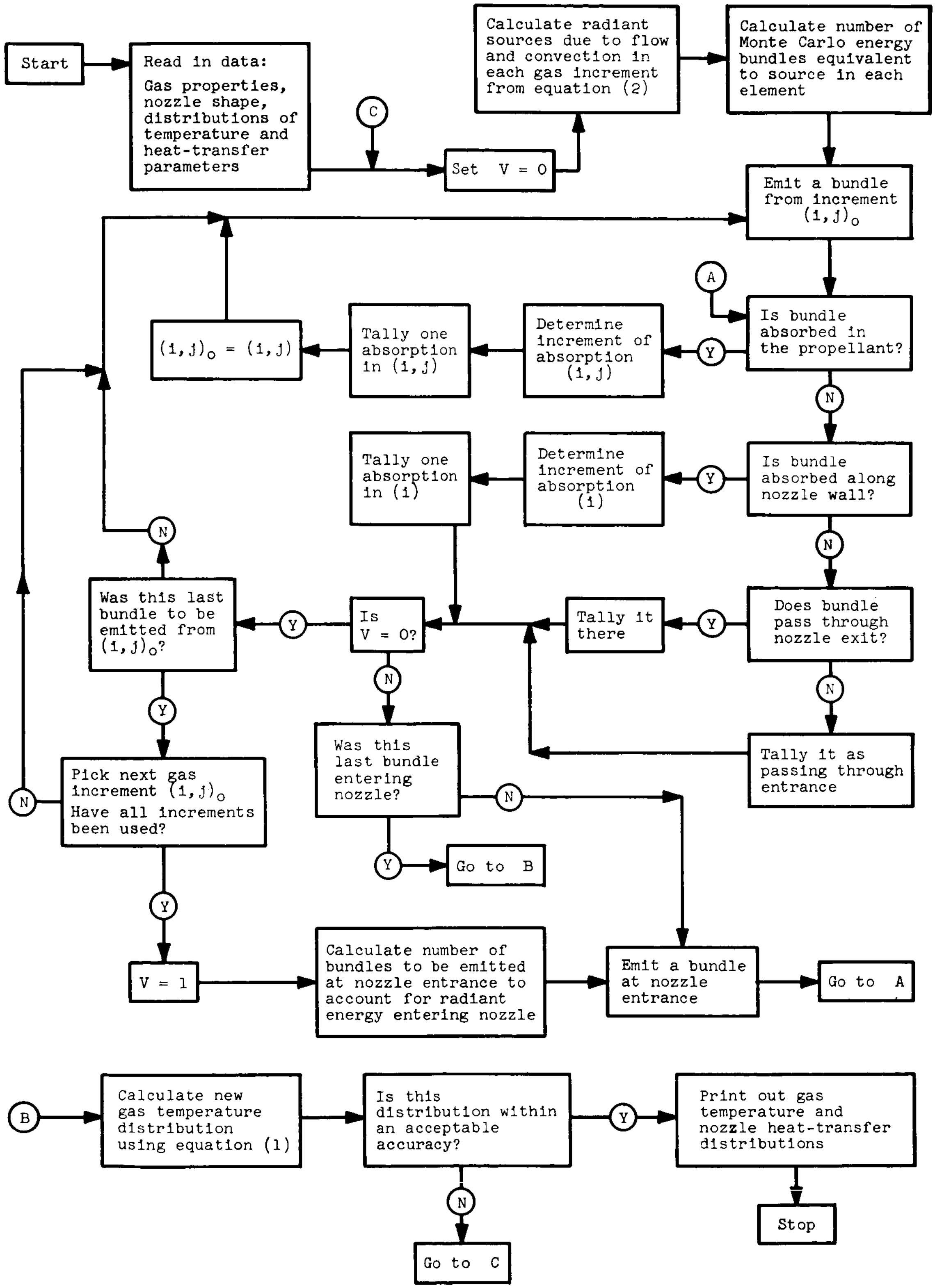

Fig. 1. - Computer flow chart.

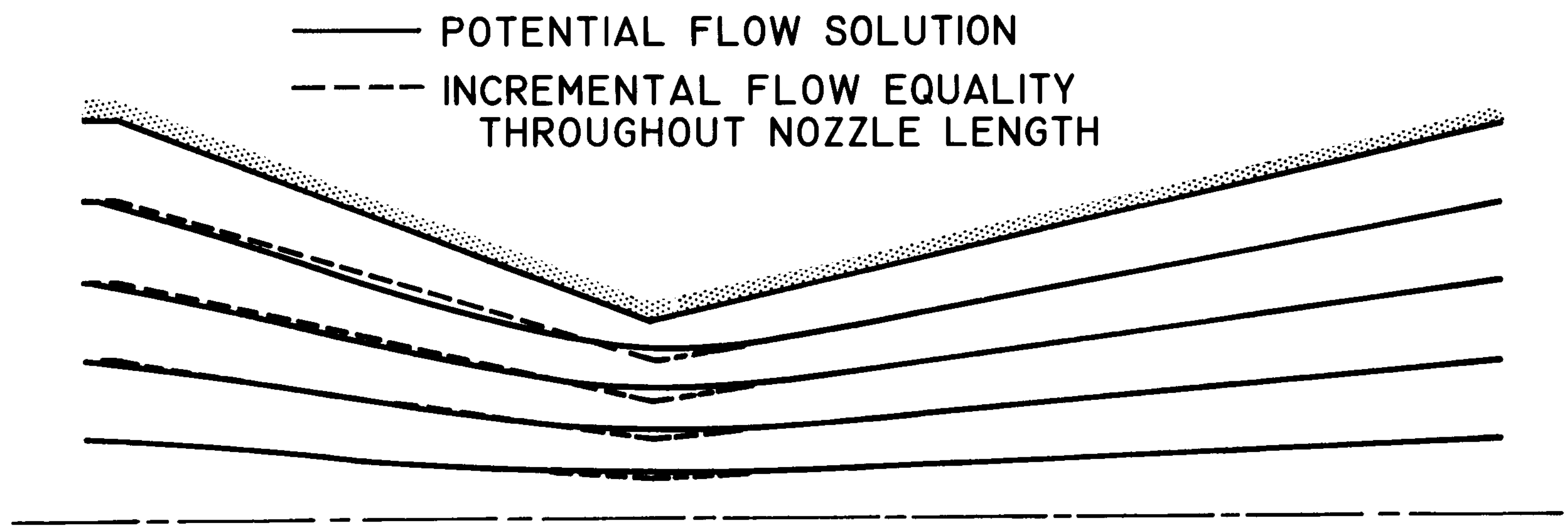

Fig. 2. - Comparison of incremental flow assumption to potential flow solution.

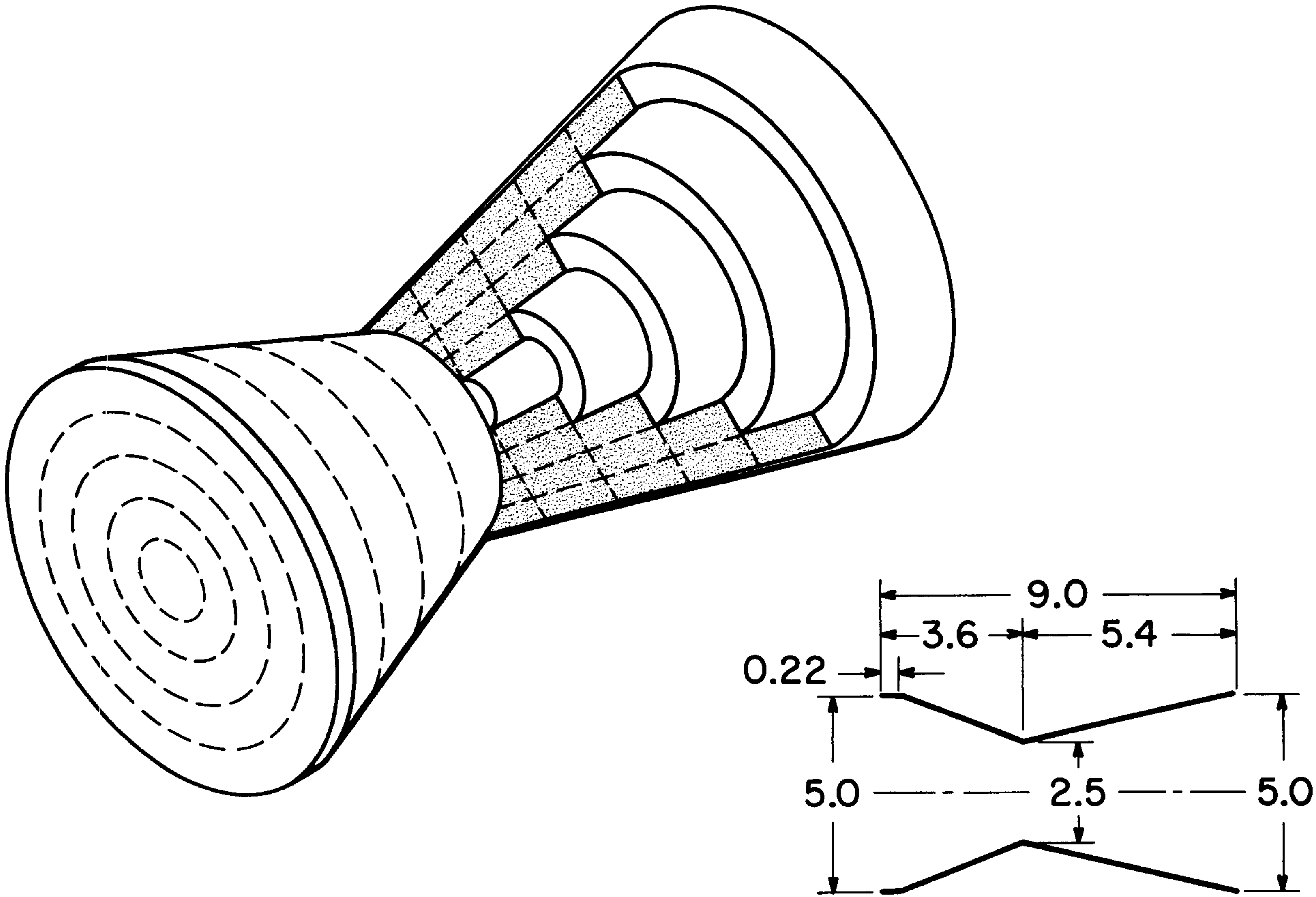

Fig. 3. - Arrangement of elements and dimensions of example nozzle.

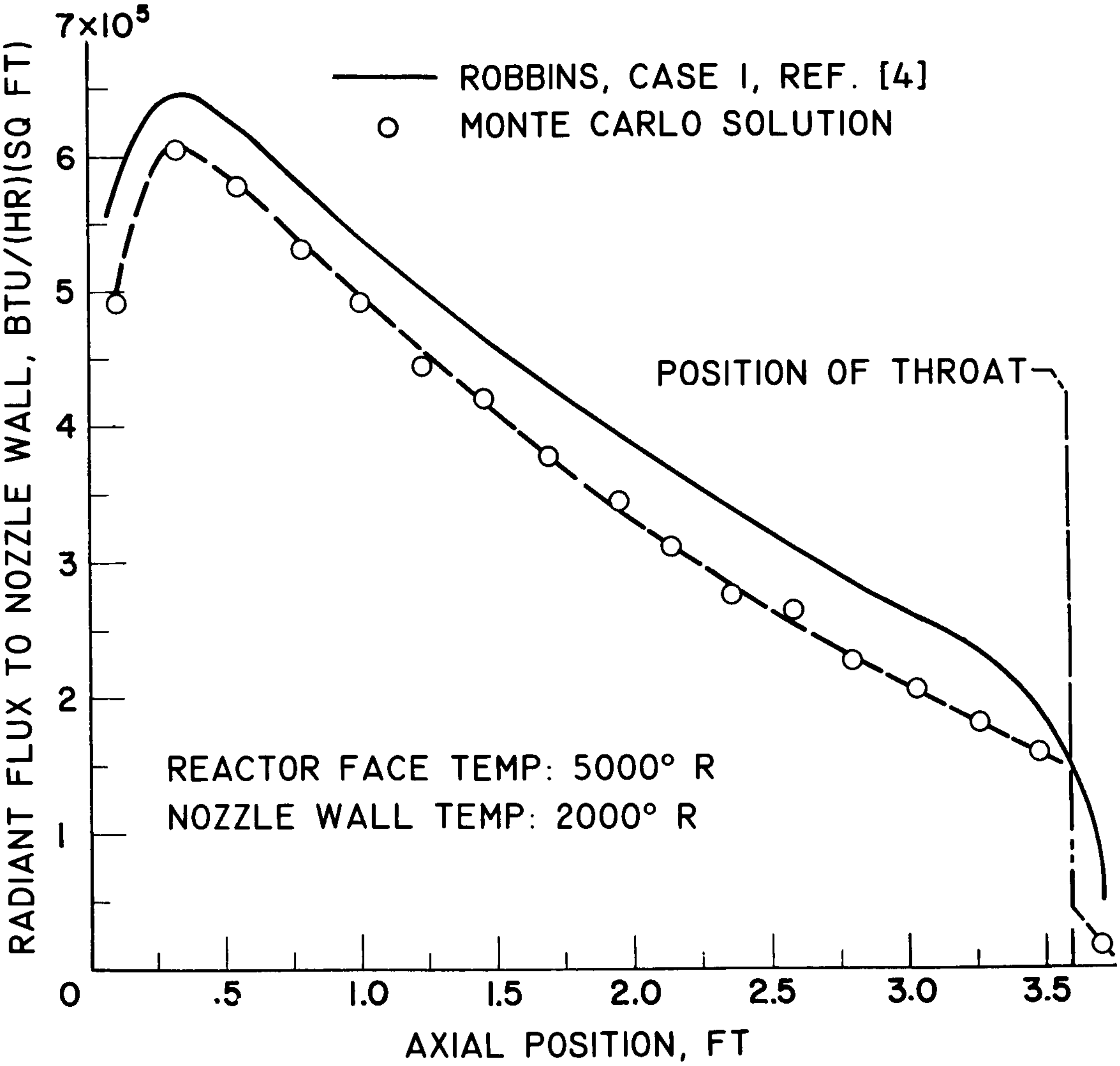

Fig. 4. - Radiant heat flux to rocket nozzle walls for transparent propellant.

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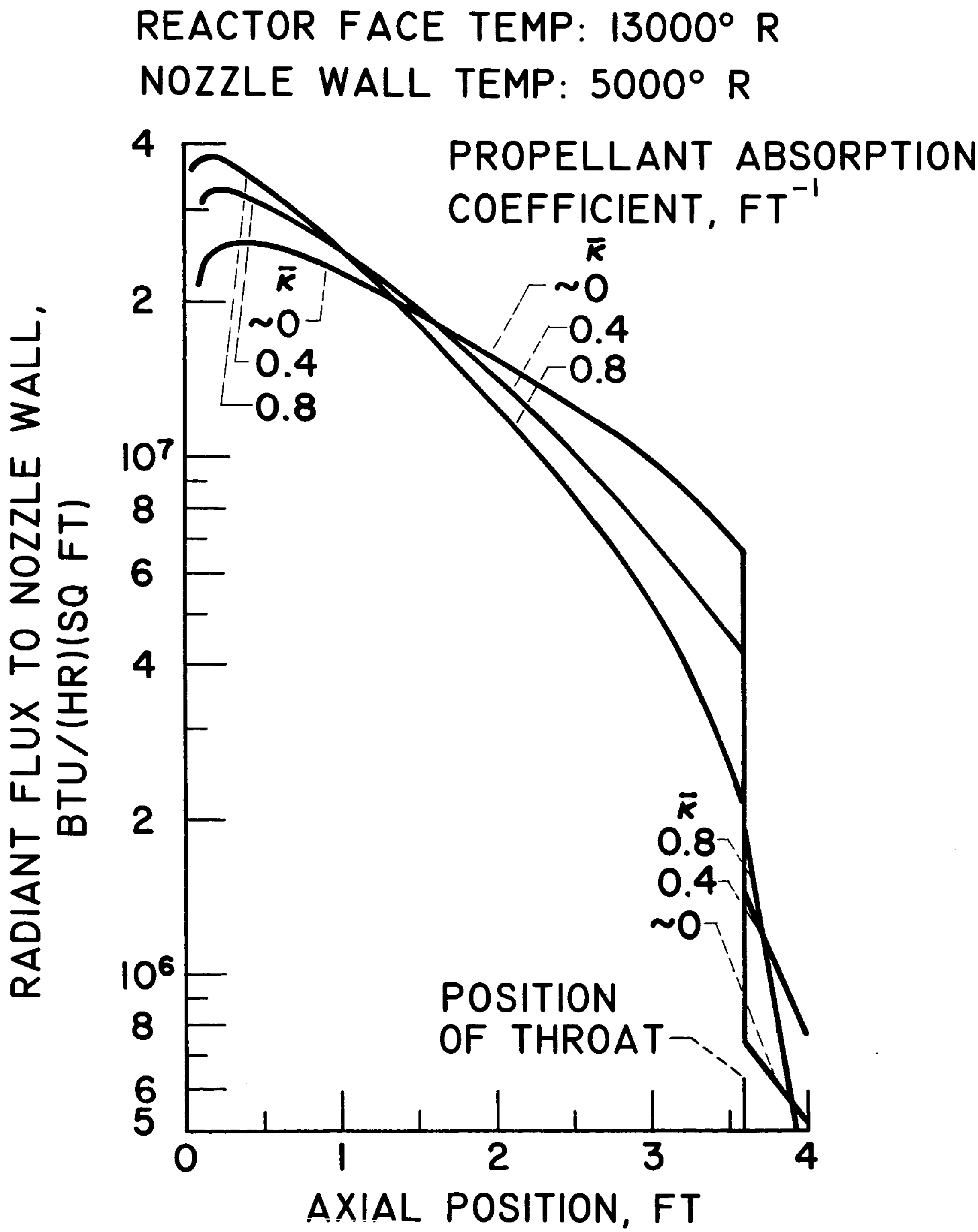

Fig. 5. - Effect of propellant absorption coefficient on nozzle wall heat flux. No flow.

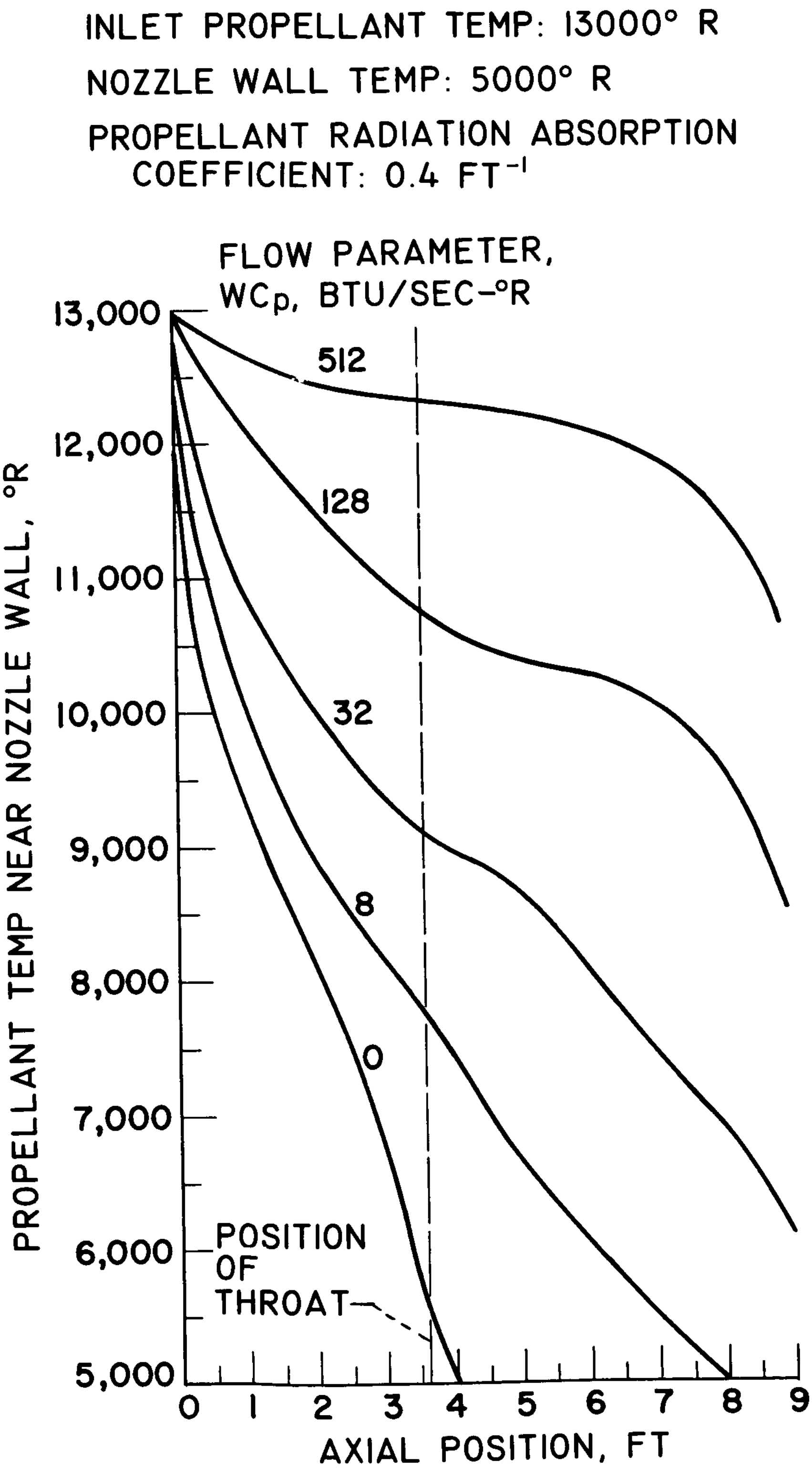

Fig. 6. - Effect of flow parameter on propellant temperature.

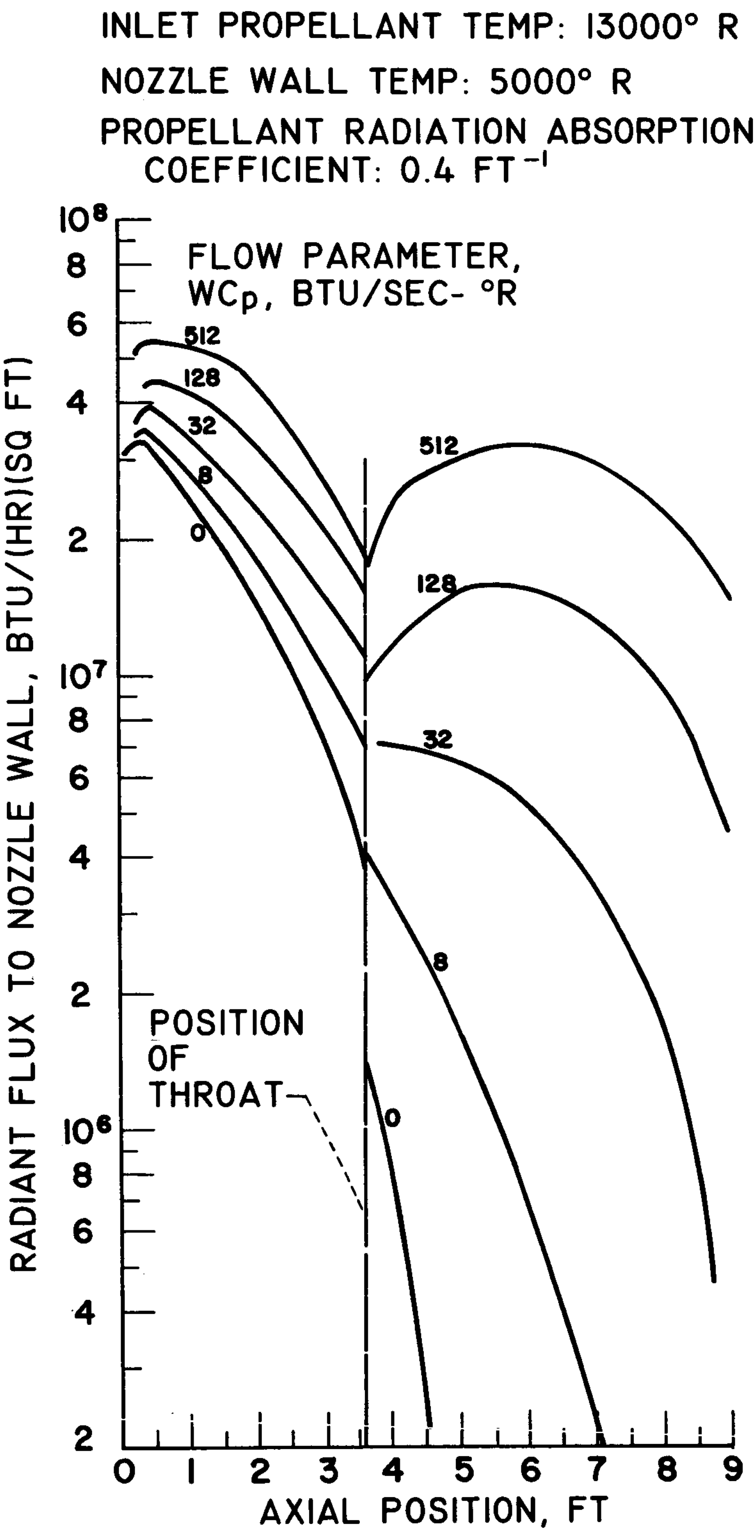

Fig. 7. - Effect of flow parameter on radiant energy flux to nozzle wall.

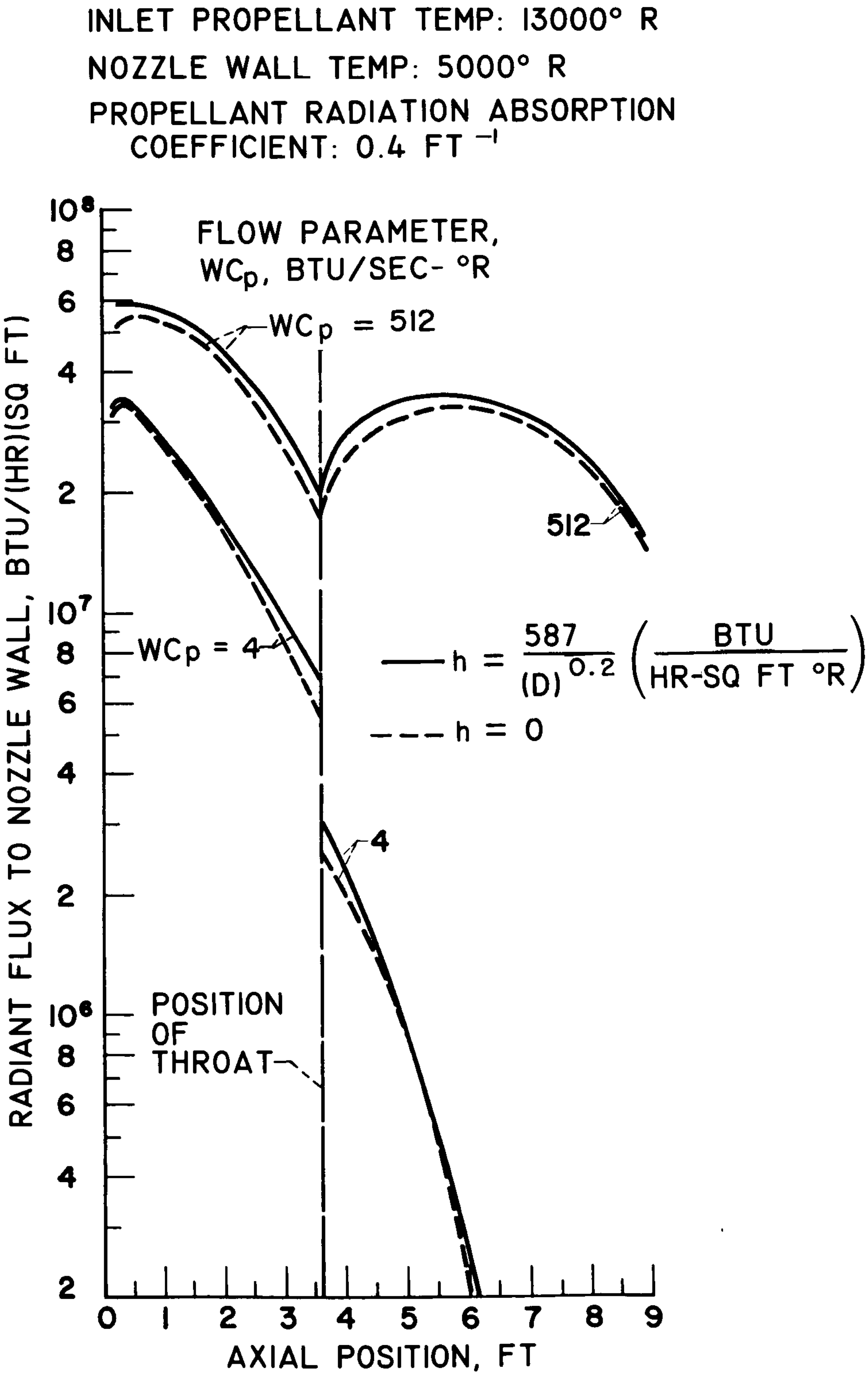

Fig. 8. - Effect of convective heat-transfer coefficient, h, on radiant energy flux to nozzle wall.